# Influence of coating thickness and sand fineness on mold filling in the lost foam casting process

M. SANDS, S. SHIVKUMAR
*Department of Mechanical Engineering, Worcester Polytechnic Institute, Worcester, MA 01609-2280, USA*
*E-mail: shivkuma@wpi.edu*

The effects of coating thickness and sand fineness on the mold filling characteristics of aluminum alloy 319 have been investigated. Experiments have been conducted with strip patterns and transparent molds have been used to visually record the flow behavior. The results indicate that a higher fill time is observed in thicker coatings and finer sands. Typical flow velocities are on the order of 80 mm/s and 90 mm/s for sands with AFS numbers of 80 and 20 respectively. By comparison, when a completely impermeable mold is used, the flow velocity is reduced to about 20 mm/s. Under normal casting conditions, the gases formed at the metal front are eliminated rapidly into the sand, so that there is no substantial gas layer ahead of the flowing melt. A gas layer may build up at the metal front if the permeability of the mold medium is not adequate and eventually the gas bubbles may escape by penetration through the liquid metal. Factors affecting polymer degradation may have strong effect on mold filling while parameters associated with the elimination of degradation products may control defect formation. © *2003 Kluwer Academic Publishers*

## 1. Introduction

Mold filling in the lost foam casting process is largely governed by the polymer degradation at the metal front. The formation and the elimination of the degradation of the products through the mold have a significant effect on the filling behavior [1]. It has been established that the degradation of the polymer (typically, expanded polystyrene, EPS) yields gaseous products and a viscous residue [2]. The composition of the gaseous products depends on the melt temperature and at about 750°C consists of styrene, benzene and other hydrocarbons [3]. The volume of gases produced is on the order of 0.2 m$^3$ (STP)/kg of EPS at 750°C. The volume of gases increases significantly with temperature. The viscous residue consists predominantly of dimer, trimer, tetramer and other oligomers [4]. A large fraction (>60%) of the solid EPS is initially converted to a viscous residue at the metal front. This viscous residue may penetrate the pores in the coating and will eventually undergo further depolymerization to yield gaseous products. These gases are then transported into the sand. Gaseous products formed at the metal front may be eliminated through the pores of the coating and into the sand. The rate of elimination depends on several factors including the volume of gases produced, effective permeability of the coating and sand, thermal properties of the coating and sand and the melt temperature [5]. From a practical point of view, mold fill times are controlled by the rapid elimination of gases into the sand and the gas permeability of the coating and the sand play a vital role in this transport. The purpose of this contribution is to examine mold filling in the lost foam process for various levels of gas permeability in the mold. The effective permeability was varied by changing the coating thickness on the polymer or by adjusting the particle size distribution in the sand. Experiments have been conducted under conditions corresponding to a broad range of permeabilities.

## 2. Experimental procedure

A schematic of the test pattern used to study the mold filling characteristics is shown in Fig. 1 [6]. A strip, 175 mm long and 40 mm × 13 mm in cross section, was attached to a gating system consisting of a hollow downsprue and a pouring basin. The hollow downsprue was 40 mm × 40 mm in cross section and had a wall thickness of 5 mm. The gating system and the strip were cut from EPS boards with a nominal density of 20 kg/m$^3$. The typical extent of bead fusion in the EPS board is shown in Fig. 2. The patterns were coated with a commercial coating, Styrokote 145.3. In order to study the effects of coating permeability, experiments were conducted with various coating thicknesses on the polymer pattern. The coating thickness on the dried pattern was varied from 0.1 mm to 0.26 mm.

The coated pattern was instrumented with chromel-alumel thermocouples. The diameter of the bare chromel and alumel wires was equal to 0.5 mm. The chromel and alumel wires were embedded in an alumina tube. Up to 15 thermocouples were used in a single experiment. The two thermocouple wires were either welded to form a bead at the hot junction (closed
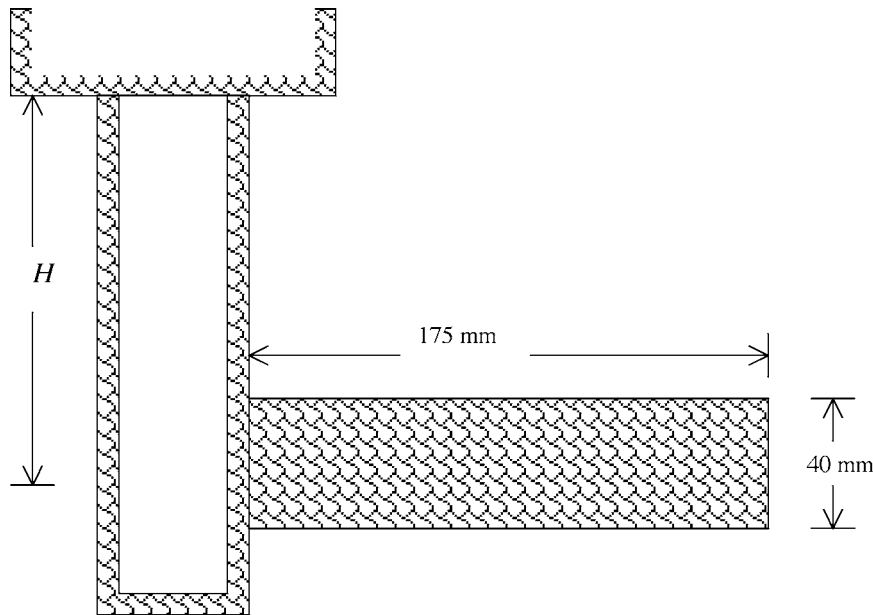
*Figure 1* Schematic of the test pattern. The test strip was glued to a hollow downsprue. In different experiments, the metallostatic head (H) was varied from 60 to 360 mm.
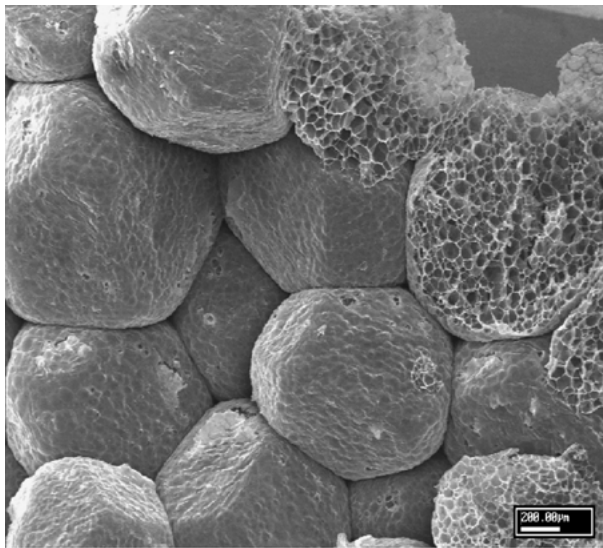


*Figure 2* Photograph showing the typical bead size, morphology and extent of bead fusion in the EPS boards used to prepare the test pattern shown in Fig. 1 [1].

thermocouple) or left in open circuit (open thermocouple) [7]. The open thermocouple only detects temperature after the arrival of the metal front while the closed thermocouple registers the complete thermal history at the given location. During the experiments, a pair of closed and open thermocouples was positioned at the same location from opposite sites of the plate (Fig. 3). Such pairs of open and closed thermocouples were placed at various locations in the pattern in order to study the filling behavior. The thermocouples were connected to a data acquisition system to study the mold filling behavior.

The mold medium was varied to obtain different values of gas permeability. In most experiments, the coated pattern was placed in a steel molding box which was partially filled with unbonded silica sand. The

thermocouples were positioned at the desired locations. After positioning the thermocouples in the pattern, the box was filled with unbonded sand and compacted by pneumatic vibration techniques. Experiments were conducted with sands with AFS numbers of 20, 55 and 80. In order to study the filling behavior under extreme conditions of gas permeability, the following procedure was used. A glass mold of the desired dimensions was used to surround the polymer pattern. This condition corresponds to metal flow into an essentially impermeable mold. In some experiments, a mold was constructed out of a porous ceramic foam filter around the polymer pattern in order to study the filling behavior in highly permeable molds. Reticulated alumina foam filters with 1200 and 800 pores/m were used in different experiments. All the experiments were conducted with aluminum alloy 319 at a pouring temperature of 760°C.

## 3. Results and discussion

Typical thermocouple outputs for various conditions are shown in Fig. 4. The thermocouples are initially at room temperature and subsequently increase to the temperature of the molten metal. The closed thermocouples often detect the transitions within the polymer. For example, inflexion points were often observed at about 100°C and at about 160°C corresponding to the collapse and melting of the polymer respectively [1]. An inflexion point is also detected in some cases at about 400°C, corresponding to the entrapment of a gas bubble at the thermocouple junction. In general, the closed thermocouples switch earlier than the open thermocouples. The difference in switching time between open and closed thermocouples positioned at the same location was below 0.5 s. The recorded temperature histories did not show any discernable effect of permeability on the switching times between open and closed thermocouples.
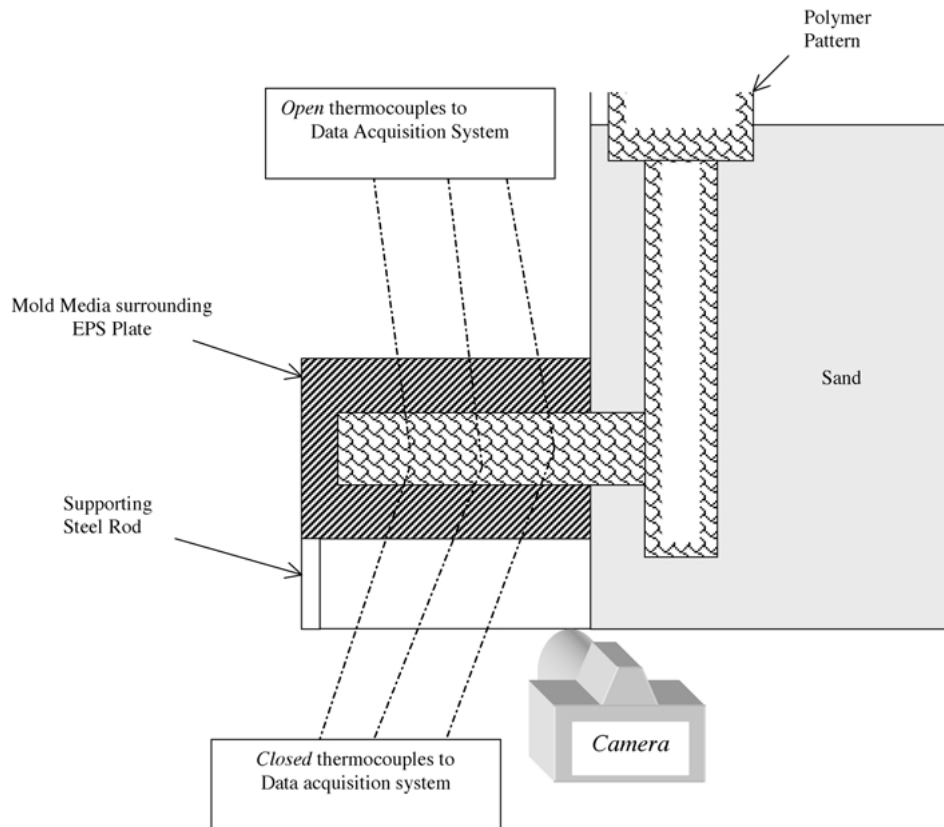
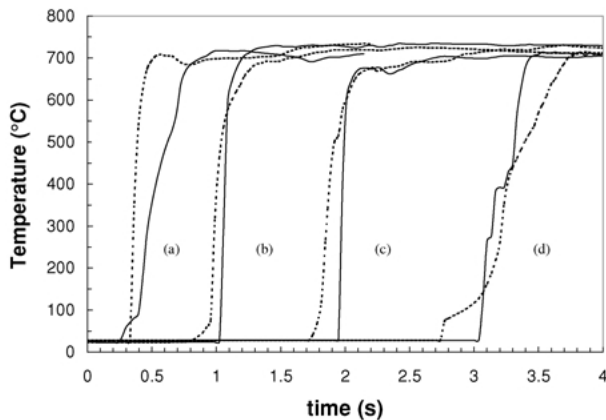*Figure 3* Schematic of the experimental set-up.



*Figure 4* Typical thermocouple outputs. (----) Closed thermocouple (——) Open thermocouple. (a) No coating, AFS 55 (b) Coating thickness = 0.19 mm, AFS 55 (c) Coating thickness = 0.19 mm, alumina filter mold (1200 pores/m) (d) Coating thickness = 0.19 mm, Glass mold.

The mold medium in the lost foam process consists of a ceramic coating whose thickness is typically on the order of 0.1 to 0.2 mm and of loose unbonded sand. The effective gas permeability of the combined mold medium is governed by the individual permeabilities of the coating and the sand. The coating permeability is influenced by several parameters including composition, size, shape and distribution of ceramic particles, amount of volatiles, thermal diffusivity and the effective thickness. Manufacturers of commercial coatings generally supply a premixed slurry to the casting manufacturer so as to attain a desired range of permeabilities. Under shop floor conditions, a specific value of permeability that is needed for a part is often obtained by adjusting the thickness of the dried coating on the EPS pattern. The effect of coating thickness on the flow behavior is shown Figs 5 and 6. In general, the fill times increase with the thickness of the coating. For example, the fill times for conditions corresponding to no coating and a coating thickness of about 0.31 mm have been measured to be 1.4 s and 2.0 s respectively (Fig. 5).

Although ceramic coatings were used initially to improve the surface finish in the casting, it is now recognized that various transport phenomena associated with
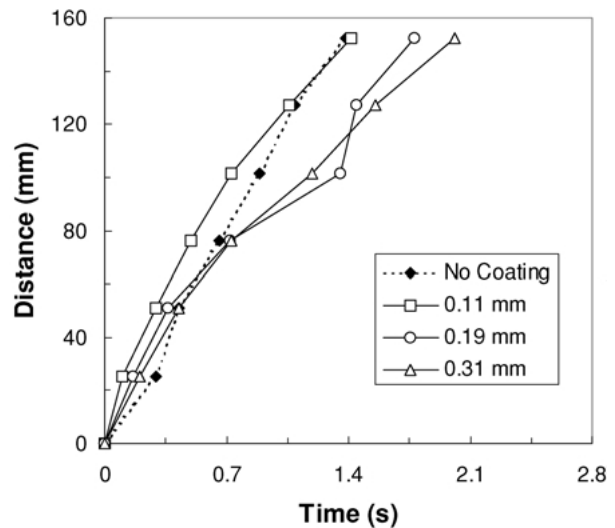


*Figure 5* Variation of distance of flow with time for a metallostatic head of 360 mm. Data for various coating conditions are shown (Sand = AFS 55).
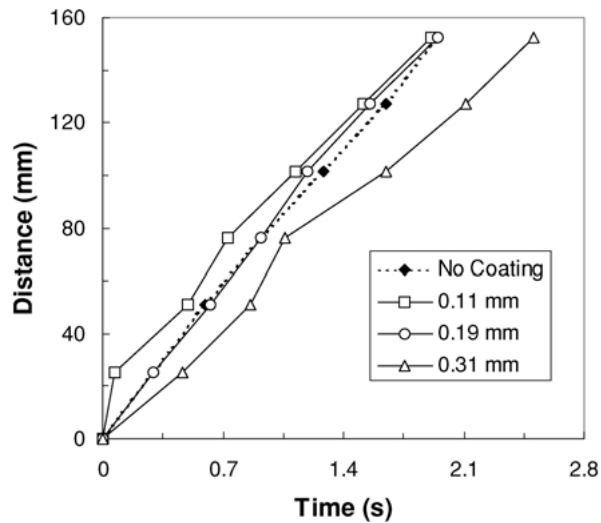
*Figure 6* Variation of distance of flow with time for a metallostatic head of 60 mm. Data for various coating conditions are shown (Sand = AFS 55).



*Figure 7* Variation of distance of flow with time for a metallostatic head of 360 mm. Data for various mold media are shown. The AFS numbers correspond to silica sand. Alumina filter 1: 1200 pores/m, Alumina Filter 2: 1600 pores/m (Coating thickness = 0.19 mm).

the coating play a major role during mold filling and solidification. The coating material provides an insulating effect during heat transfer and therefore reduces the rate of cooling in the liquid metal. Heat transfer coefficients at the metal-mold interface have been measured to be 570 $W/m^2 \cdot K$ in uncoated and 420 $W/m^2 \cdot K$ in coated specimens [4]. As a result, the application of the coating on the polymer pattern improves the fluidity [8]. The coating also controls the rate of elimination of the degradation products into the mold. The gaseous degradation products formed at the metal front are eliminated into the sand through the pores in the coating. The coating is designed to absorb the partially depolymerized viscous residue formed at the metal front [6]. This absorption of the viscous residue by the coating may close some of the pores in the coating and thus affect gas permeability. If too much of the viscous residue accumulates at a location, the local gas permeability may be adversely affected. In this case, the gases may not be eliminated into the mold rapidly and this may contribute to defect formation in the casting during solidification [9]. The thermal properties of the coating play a vital role in this elimination process [5]. If the coating is not heated rapidly, the gaseous degradation products may condense readily in the pores in the coating and reduce the effective gas permeability.

The flow behavior in various mold media is shown in Figs 7 and 8. It is observed that under typical casting conditions, there is a slight increase in fill times as the permeability is decreased. For example at a metallostatic head of 360 mm, the fill time for a length of 150 mm is on the order of 1.8 s and 1.9 s for sands with AFS numbers of 20 and 55 respectively. When the gas permeability is increased substantially by using alumina filter molds, the fill time changes to about 1.15 s. Clearly, under extreme conditions, where the elimination of gases through the mold medium is totally eliminated (by the use of a glass mold), the fill time is increased substantially to about 7 s.

The data shown in Fig. 9 indicate that the extent of gas layer ahead of the metal front is small, generally less
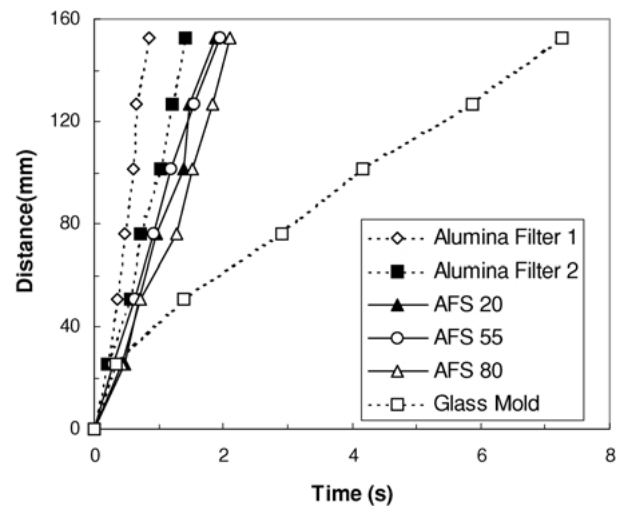


*Figure 8* Variation of distance of flow with time for a metallostatic head of 60 mm. Data for various mold media are shown. The AFS numbers correspond to silica sand. Alumina filter 1: 1200 pores/m, Alumina Filter 2: 1600 pores/m (Coating thickness = 0.19 mm).
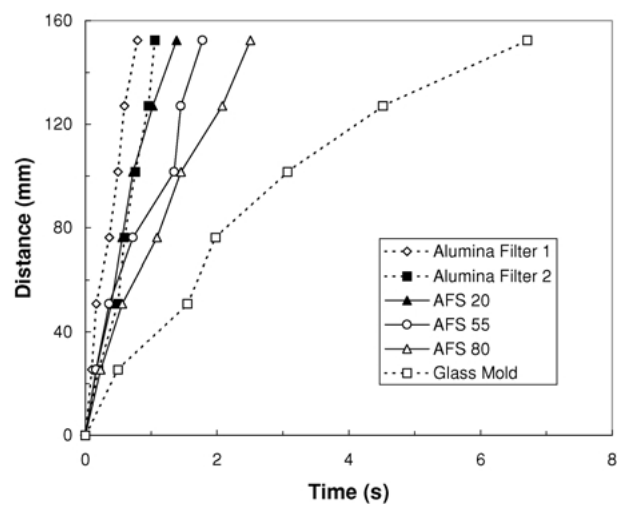
than 1 to 3 mm, indicating that gases produced at the metal front are eliminated rapidly into the mold. Similar behavior was observed for all the coating thicknesses and for the three sands (AFS 20, 55 and 80) used in this study. However, if the local conditions in the mold affect gas permeability by coating build up, sand particle agglomeration, or accumulation of fines, the rate of gas elimination is affected adversely. If the local permeability is not adequate for the complete elimination of the gases formed, a gas layer may buildup ahead of the metal front. A substantial gas layer can be seen ahead of the metal front for the extreme case of a glass mold as shown in Fig. 10. The photographs of Fig. 10 show that the thickness of the gas layer in this case is on the order of 10 to 15 mm. The thickness of this gas layer may be estimated from the flow velocity. The flow velocity for this condition can be calculated from Fig. 7 to be on the order of 20 mm/s. Using the difference in switching times for the closed and open thermocouples
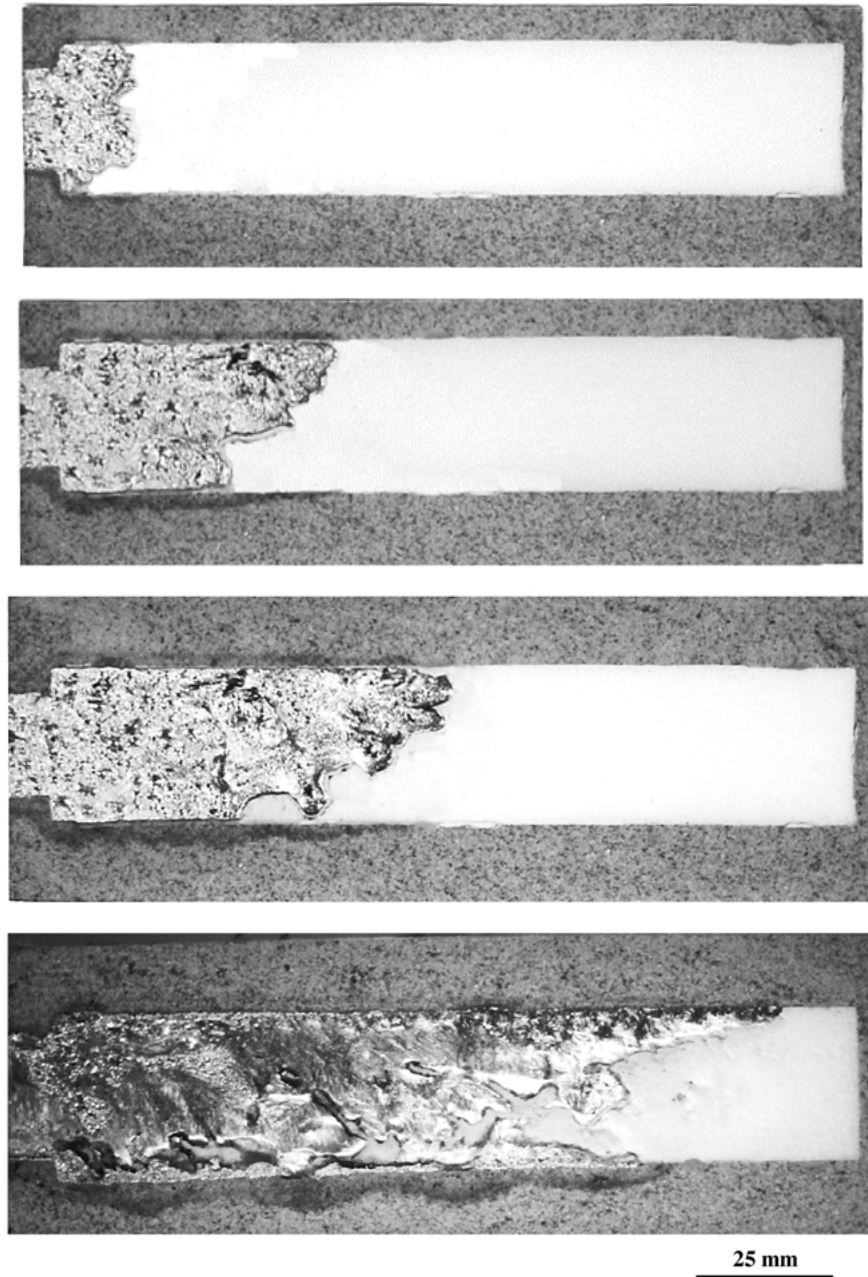
*Figure 9* Sequential photographs showing the flow of the liquid metal into the polymer pattern. (AFS 55 sand).

of 0.45 s, the thickness of the gas layer can be estimated to be on the order of 10 mm, in agreement with the preceding data. A large gas layer at the metal front cannot be supported as the gas pressure in this layer may lead to the penetration and eventual escape of the gas bubble through the melt and the gating system. However, the endothermic losses at the metal front lead to rapid cooling of the metal and the gas bubble may be trapped in the solidifying metal. A large number of gas bubbles, whose size was on the order of 0.5 to 2 mm were observed in the casting produced with the glass mold. Hence, the approximate overpressure ($\Delta P$) needed for penetration of the gases into the melt can be obtained using the following equation, $\Delta P \approx 2\gamma/r$, where $\gamma$ is the surface tension of the liquid metal and $r$ is the radius of the bubble. The surface tension of liquid Al is about 900 mN/m, from which, $\Delta P$ is on the order of 0.01 to 0.03 atm [10].

The gases transported through the coating may condense in the sand. A distinct condensed gas layer is observed in the photographs shown in Fig. 9. If the mold medium has a high permeability, the gases may travel significant distances before condensing. For example, the gaseous products travel over 20 mm to escape through the porous alumina mold as shown in Fig. 11. Hence, the permeability of the mold media may dictate the penetration distance of the gaseous degradation products before the onset of condensation. The data shown in Fig. 11 are for an extreme condition typically not encountered in commercial practice. Under practical conditions, however, it can be expected that the permeability is not as large as it is in the alumina filter mold shown in Fig. 11. Under these conditions, the gases condense in the sand over relatively short distances (Fig. 9) and further transport of the condensed products is determined by the rate of temperature increase in the
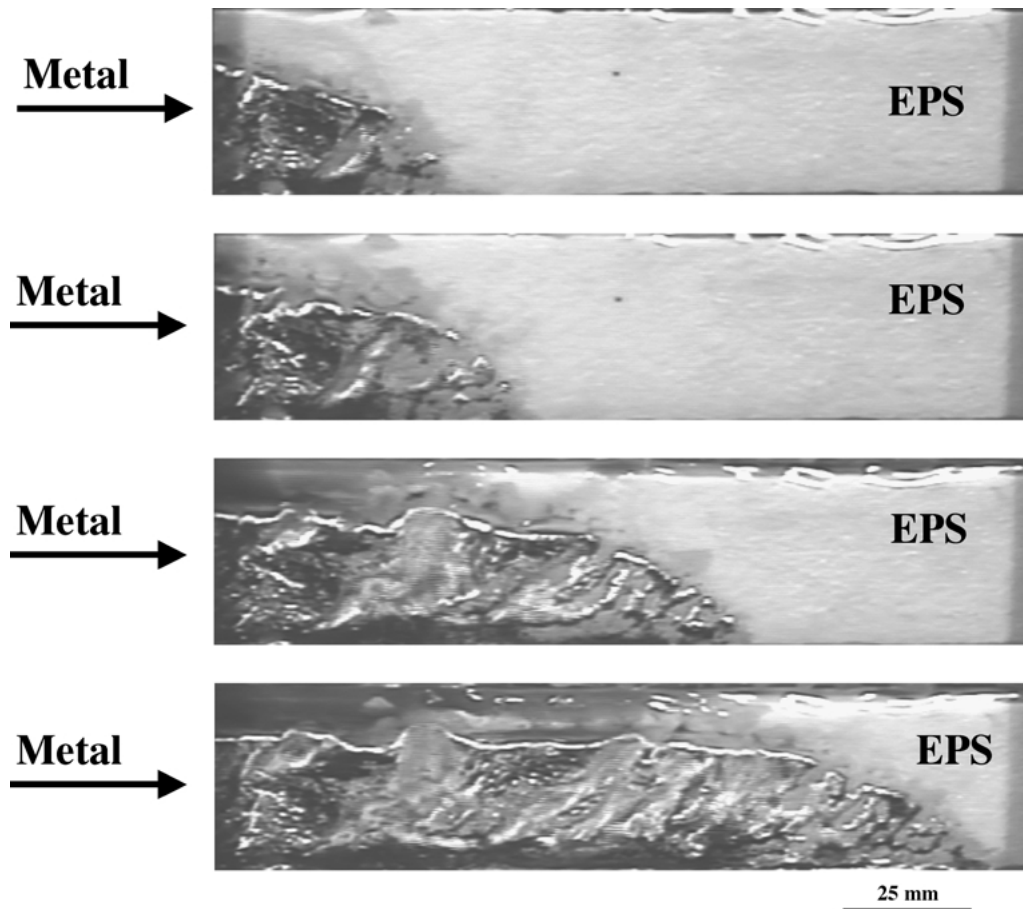
*Figure 10* Sequential photographs showing the flow of the liquid metal into the polymer pattern. (Glass mold).

sand. As the temperature of the sand increases, the condensed products revaporize and penetrate further into the sand. This sequence of condensation-vaporization-condensation for the elimination of the gaseous degradation products into the sand has been observed previously [5]. In this case, the thermal properties of the sand also become important in the elimination of the degradation products.

Mold filling in the lost foam process is determined by the nature of depolymerization processes that dictate the composition of the degradation products and by the subsequent elimination of the degradation products. The results presented here indicate that the kinetics of depolymerization of EPS are more significant during mold filling than the rates of elimination of degradation products. Consider for example, the flow of aluminum melt in an empty-cavity mold. In this case, the flow velocity can be approximated to be $\sqrt{2gh}$, where $h$ is the metallostatic head. The flow velocity in an empty cavity mold for the conditions shown in Fig. 7 is on the order of 2.6 m/s. By comparison, the flow velocity in lost foam molds is measured be about 100 mm/s. Improving the permeability significantly by using porous alumina filters leads to a small increase in flow velocity to about 150 mm/s. Similarly, under extreme conditions where an impermeable glass mold is used, the flow velocity is on the order of 25 mm/s. In this case, the gas layer ahead of the metal front may hinder the heat transfer from the metal to the polymer and thereby lower the rate of metal flow into the pattern. It appears that the commercial coatings generally have sufficient gas permeability to eliminate the gases rapidly and may have a limited effect on mold filling. Therefore, the rate limiting step during mold filling that determines the overall filling time is the depolymerization of the EPS pattern. Hence, parameters associated with the degradation of the pattern are likely to have a significant effect on mold filling, while factors controlling the elimination of the degradation products are important in defect formation. The melt temperature is one of the most important parameters that influence the nature of the degradation process. Filling times have been measured to be 44 s and 1.85 s for melt temperatures of 200°C and 750°C [2]. Further, the rate of gas production increases with temperature as the polymer molecule undergoes additional fragmentation. The gas yield (volume of gases produced per unit mass of polymer) is on the order of 0.2 and 0.8 m³(STP)/kg of foam pattern at 750 and 1300°C respectively. Consequently, the coating permeability needs to be changed to accommodate the higher gas production as the temperature is increased. It should be noted that other factors, mostly related to the polymer pattern, can also influence the rate of gas production. The rate of gas production (and hence, the fill time) is proportional to the density of the foam pattern [11]. It has also been shown that the average molecular weight of the polymer and the polydispersity index may have a significant effect on the rate of gas production.
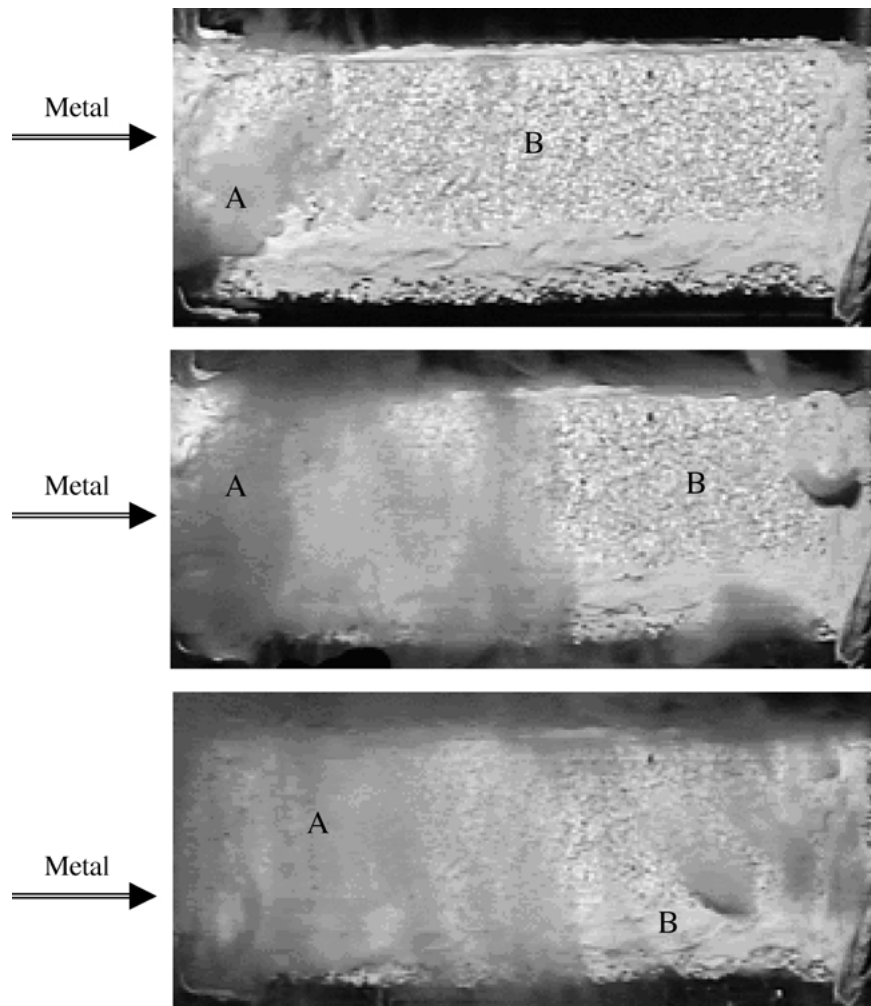
*Figure 11* Sequential photographs during various stages of filling in a porous alumina filter mold (Alumina foam filter 1600 pores/m). Note that the gaseous degradation products (A) are escaping through the porous alumina mold (B). The polymer strip was surrounded by the alumina filter mold. The thickness of the alumina filter around the polymer was typically on the order of 20 mm.

## 4. Conclusions

The mold fill time generally increases with the thickness of the coating. A higher fill time is also observed in finer sands. The extent of this variation in fill time is typically less than 50% of the value measured under normal conditions encountered in commercial practice. However, under extreme conditions, where the mold is almost impermeable, the gases have to escape through the melt and hence, in this case, the fill time increases by over 500% of the normal value. Such a situation can exist at locations where there is a coating buildup on the pattern or where there is local agglomeration of the sand due to condensation of degradation products, and is conducive to defect formation. The gas layer at the metal front may be very small, typically less than 1 to 3 mm. Gas layer thicknesses of up to 15 mm have been observed in molds that are not permeable. Mold filling in the lost foam process is determined by both the formation and the elimination of degradation products. The thermal degradation of the pattern has a greater influence on fill time than the physical phenomena associated with the elimination of the degradation products. Factors controlling pattern degradation such as melt temperature, molecular weight and polymerdensity are likely to have a strong effect on mold filling while factors associated with the elimination of degradation products are likely to govern defect formation.

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